

An Integrated Design of Hydrothermal Liquefaction and Biogas Plant For The Conversion of Feedstock (Biomass) To Biofuel

A Project Report Submitted

by

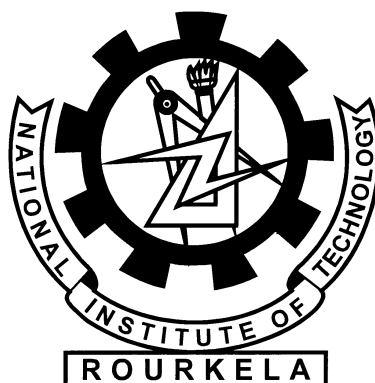
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CERTIFICATE

This is to certify that the project entitled **An integrated design of hydrothermal liquefaction and biogas plant for the conversion of feedstock (biomass) to biofuel**,
Submitted by **Abhishek Maharana** is a bonafide work done under my supervision.

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ABSTRACT

A study of low quality biomass conversion to high quality diesel like fuel is studied in aspen simulation. The simulation is carried out in four section i.e. biogas plant, hydrothermal liquefaction unit (HTL), hydrogen producing unit (HPU), upgrading unit (UU). The primary goal of this project is to derive a conceptual design of the plant and estimate the feasibility of the process. In this process, biomass gets converted to biogas and digestate in biogas plant. The biogas is sent to HPU and digestate is sent to HTL unit where it is converted to biocrude under high temperature and high pressure. In HPU, Methane steam recovery is done to produce Hydrogen which is used for reforming biocrude to high quality diesel, i.e. biofuel. An input of 1000 kg/hr biomass provides approximately 30-38 kg/hr biofuel and 38-61 kg/hr biogas. . In the period of hydrogen producing unit the effect of different parameters including temperature, pressure and ratio of steam to gas was investigated. Higher flow rate of steam is favorable for hydrogen yield. Increasing the temperature above 700°C increases the hydrogen yield and higher pressure decreases the hydrogen yield.

Keywords: Biogas plant, hydrothermal liquefaction, hydrogen producing unit, upgrading unit, CHP, Aspen Plus, Proximate analysis, Ultimate analysis,

INTRODUCTION

Hydrogen production derived from biomass gasification is proved to a competitive method to obtain environmental friendly fuel. The need for renewable and sustainable energy sources is high because of a number of factors: the increase in global energy demand, depletion of conventional resources, climate issues and the desire for national/regional energy independence. In 2010, fossil fuels still accounted for 87% of global and 79% of EU primary energy consumption. ^[4] Biomass is an important renewable energy with zero CO₂ emissions in the use of biomass gasification technology, which may construct a new way of energy utilization, and may be in line with the requirements of sustainable development. Biomass gasification is regarded as a complex process not only because the source of solid biomass is variable widely, also because multiple reactions take place in different steps, including drying, devolatilisation, pyrolysis and gasification ^[7]. Bio-refinery concepts are currently receiving much attention due to the drive towards flexible and highly efficient systems for utilization of biomass for food, feed, fuel and biochemical. One way of achieving this is through appropriate process integration, by combining enzymatic bio-ethanol production with catalytic liquefaction of the wet distillers grains with soluble and a byproduct from the bio-ethanol process. Because biomass will also be a prime feedstock for a wide range of chemical, nutritional and pharmaceutical products, it will become a limited, high-cost commodity. Therefore, for liquid biofuels to be produced in bulk, it is necessary to identify eligible low-value organic streams such as animal biomass, agro-industrial waste and sewage sludge.

Sustainable energy ^[15] is the sustainable provision of energy that meets the needs of the present without compromising the ability of future generations to meet their energy requirements. Technologies that promote sustainable energy include renewable sources, such as hydroelectricity, solar energy, wave power, geothermal energy, wind energy, and tidal, and also technologies designed to improve energy efficiency. Atmospheric carbon dioxide concentrations have been steadily increasing due to human activity in the form of burning fossil fuels and deforestation. A cleaner energy future depends on the development of alternative energy technologies to meet the world's growing energy needs but that also mitigate carbon dioxide emissions ^[13]. Being efficient with our energy will reduce our household and business energy bills, reduce the total amount of energy that is needed to produce in the first place and cut energy related greenhouse pollution. So sustainable energy is not just about using renewable energy, perhaps it's not even about renewable energy as we explain further below, it's about using energy wisely and introducing energy efficiency measures.

Renewable energy ^[13] is better for the environment. Every day energy is being consumed from a wide range of sources. An increasing amount of energy comes from renewable sources. Replacing non-renewable energy with renewable sources of energy has many benefits.

Many forms of energy that we have grown dependent on are from non-renewable energy sources. This says that when the energy has been consumed, the supply has gone and cannot be replaced. An example is coal. Coal is known as a fossil fuel and is the largest source of energy for the generation of electricity worldwide. Finding alternative energy sources, ideally from renewable sources, will substantially decrease our dependency on fossil fuels and other non-renewable energy sources. Renewable energy sources will help to reduce the dependency

on non-renewable supplies, such as fossil fuels will help produce sustainable energy options for generations to come.

Energy sustainability ^[15] will require changes not only in the way energy is being supplied, but in the way it is being used, and reducing the amount of energy required to deliver various goods or services is essential. Renewable energy and energy efficiency are sometimes said to be the “twin pillars” of sustainable energy policy. Both the resources must be developed in order to stabilize and to reduce the high carbon dioxide emissions. Efficiency slows down the energy demand growth so that rising clean energy supplies can make deep cuts in use of fossil fuel. If energy use grows too fast, renewable energy development will chase a receding target.

Renewable energy ^[13] (and energy efficiency) is no longer niche sectors that are promoted only by governments and environmentalists. The increased levels of investment and the fact that much of the capital is coming from more conventional financial actors suggest that sustainable energy options are now becoming mainstream.

Hydrothermal liquefaction (HTL) is a promising technology for converting wastewater biomass into a liquid fuel. HTL has been applied to a wide range of wastewater feedstock, which includes swine biomass, cattle biomass, microalgae, macroalgae, and sludge. During HTL, water serves as the reaction medium, alleviating the need to dewater biomass which can be a major energy input for biofuel production. Elevated temperature (200–350 °C) and pressure (5–15 MPa) are used to breakdown and reform biomass macromolecules into biofuel ^[9], subsequently referred to as biocrude oil. Self-separation of this particular biocrude oil from water is then facilitated as the reaction solution returns to standard conditions. The recovered biocrude oil can be directly combusted or upgraded to approach petroleum oils. HTL biocrude oils contain a diverse range of chemical compounds which can include aromatics, straight and branched aliphatic compounds, and phenolic derivatives, carboxylic

acids, esters, and nitrogenous ring structures. The conversion of wet biomass under hydrothermal conditions is an alternative to pyrolysis and combustion under ambient pressure. The benefits compared to conventional energy sources are CO₂ reduction and sustainability. Several types of waste biomass and fresh plants available for the production of energy and fuels are not suitable for common pyrolysis processes because of their high water content (>70%) ^[3]. For classical processes, the biomass has to be dried, which is an energy- and time-consuming step. This high cost step can be avoided by liquefaction or catalytic conversion of biomass in near-critical water.

Biogas ^[16] typically refers to a gas produced by the breakdown of matter in the absence of oxygen. Biogas is considered as a renewable energy source like other renewable energy sources as solar and wind energy. Biogas is produced by the anaerobic or fermentation of biodegradable materials such as municipal waste, green waste, biomass, sewage, plant material, and crops. The gases methane, hydrogen, and carbon monoxide (CO) can be combusted or oxidized with the component oxygen. This energy release allows biogas to be used as a fuel. Biogas can be utilized for electricity production on sewage works in a CHP gas engine, in which the waste heat from the engine is conveniently used for heating the digester; cooking; space heating; water; and process heating. Methane within biogas can be concentrated via a biogas upgrader to the same standards as fossil, which itself has to go through a cleaning process and becomes bio methane. The biogas components ^[10] which are contained in its gaseous mixture are those that make it capable for producing renewable energy. During anaerobic digestion of organic materials which contain certain groups of anaerobic bacteria and the organic substrate is converted into biogas which is a gaseous combustible mixture, and has the ability to be used in various applications for energy production ^[11]. The main compound consisted in biogas mixture is methane (CH₄) which is actually the compound that gives biogas combustible properties. In a biogas plant, organic

materials, such as animal biomass, energy crops or industrial organic sludge, are anaerobically digested to produce biogas in airtight reactors. Through this decomposition, organic bound carbon in the biomass slurry is converted primarily into a mixture of CH₄ and CO₂. Two operation modes are used: mesophilic and thermophilic digestion. Mesophilic plants digest at 35–40°C, and thermophilic plants operate at 50–60°C^[4]. The biogas produced is mainly used for CHP production, but it can also be used directly or purified to yield CH₄ for other purposes. The leftover product, the digestate, is commonly used as fertiliser on farm land. The amount of biogas obtained from the biomass feed depends on several factors: the dry matter content of the slurry, the origin of the slurry and the conditions and reaction time in the digester.

To upgrade the biocrude, hydrogen needs to be produced from part of the biogas stream. Thus, the biogas components are separated using a membrane separator. The membrane module in this simulation is simplified to consist of one multistage compression series and one membrane unit. The pre-treated feed gas (methane) is mixed with steam before entering the reforming reactor. The ratio $n_{\text{water}}/n_{\text{methane}}$ is set to 1.5^[4]. The steam methane reforming (SMR) reaction is highly endothermic and catalysed by nickel.

Three oxygen-eliminating reactions for the fatty acid model compound have been taken into account. Oxygen atoms can be removed from the carboxylic group of hexadecanoic acid in the form of water by Hydrodeoxygenation. Hydro decarboxylation leads to the elimination of a carboxylic group in the form of carbon dioxide.

The relationship between the cooling and heating utilities illustrates the high potential for process integration and the need for further development of a heat recovery system. Pending this development, the evaluation of the plant is based on the electricity needs for pumps and compressors as modeled. These utilities are covered by burning the remaining biogas (i.e., that which is not used for biocrude upgrading) partially or completely in a CHP unit,

releasing heat that is supplemented by burning the offgas from the HP and upgrading unit in a gas boiler. The plant design offers possible solutions for and simplification of the issues of existing biogas plants. Because the digestate is directly converted after production in the biogas plant, no large storage tanks are necessary; the disposal problem could be solved, and at the same time fertilizer could be extracted from the waste water.

CHAPTER-2

LITERATURE REVIEW

Elliott et al. (1989) studied that renewable resources can provide a substantial energy resource. Liquids are preferred for use as transportation fuels because of their high energy density and handling ease and safety. The processing temperature is generally in the range of 350°C with operating pressures in excess of 1000 psig. Because of the chemical differences in the two products described above, different upgrading schemes have been derived for converting the products into usable hydrocarbon fuels. Catalytic hydroprocessing is an obvious choice based on the existing knowledge of sulfur removal from petroleum products. The reactor system includes gas feed from a high-pressure (6000 psig) bottle, oil feed by positive displacement pump, a 1-liter reactor vessel containing 850 mL of alumina-supported metal sulfide catalyst (sulfided in place), pressure control by a back-pressure regulator, and product recovery in a cooled, atmospheric-pressure gas-liquid separator. The extent of saturation as shown by the H/C ratio is a useful indicator of the aromatic character of the product. By nuclear magnetic resonance (NMR) of carbon-13, similar component groups can be identified and quantified.

Ahmad et al. (2010) studied that bio-oil is an alternative energy source produced from pyrolysis of biomass. This study aimed to investigate feasible routes and to develop the process route to upgrade the pyrolytic bio-oil from biomass into value-added chemicals for the production of transportation fuel, i.e., benzene and cyclo-hexane. Hydrodeoxygenation (HDO) is one of the examples of the hydrotreatment process in which hydrogen is used to

reduce the high oxygen content in bio-oil in the presence of suitable catalysts such as Cobalt-Molybdenum (CoMo) or Nickel-Molybdenum (NiMo) sulphides. The bio oil from the biomass fast pyrolysis is upgraded via HDO which consists of two stages. The vapor phase is compressed to the operating pressure of 8.6 MPa before entering conversion reactor 1 as a liquid-vapor mixture with a vapor fraction close to 1. The operating pressure of the product stream from reactor 2 is reduced using a valve to 3.4 MPa before the stream is heated to 400°C prior to its entrance into the third conversion reactor.

Vardon et al studied the influence of wastewater feedstock composition on hydrothermal liquefaction (HTL) biocrude oil properties and physico-chemical behaviour. Spirulina algae, swine biomass and digested sludge were changed under HTL conditions (300°C, 10–12 MPa, and 30 min reaction time). Biocrude yields ranged from 9.4% (digested sludge) to 32.6% (Spirulina). During HTL, water serves as the reaction medium, alleviating the need to dewater biomass which can be a major energy input for biofuel production. Elevated temperature (200– 350 °C) and pressure (5–15 MPa) are used to breakdown and reform biomass macromolecules into biofuel, subsequently referred to as bio crude oil. Samples were converted into biocrude oil under hydrothermal conditions (300 °C, 10–12 MPa, and 30 min retention time) in single runs for each feedstock using a Parr 4500 2-L reactor. Detailed multi-method characterization demonstrates that feedstock organic content and nutritional composition greatly affect HTL biocrude oil yields and chemistry, despite having similar bulk elemental distributions. The molecular-level information obtained from complementary methods can also help researchers design functional group-specific chemical strategies and processes to further reduce heteroatom content and improve HTL biocrude properties.

Schmidt et al studied the catalytic reaction of wet organic matter at near-critical water conditions ($T > 300^{\circ}\text{C}$, $p > 22.1\text{ MPa}$) is used to produce a mixture of combustible organics which can be used as liquid biofuel. In order to achieve a better product quality in a continuous step process, two catalysts were applied, one homogeneous potassium carbonate catalyst and a heterogeneous ZrO_2 catalyst. The conversion of wet biomass under hydrothermal conditions is an alternative to pyrolysis and combustion under ambient pressure. The catalytic reaction of wet organic matter—without drying— under near-critical water conditions ($374^{\circ}\text{C} > T > 300^{\circ}\text{C}$, $p > 22.1\text{ MPa}$) is used to produce a liquid biofuel. In order to obtain a good product quality in a continuous, one-step process, two different catalysts were applied, a homogeneous potassium carbonate catalyst dissolved in the feed stream and a heterogeneous ZrO_2 catalyst in a fixed-bed reactor. The biomass stream is heated very quickly from a lower temperature (e.g. 250°C) by mixing with the hot recirculation stream (e.g. 330°C). Throughput of the recirculation stream is higher. The feed flow is heated up to the temperature required for the reaction ($300\text{--}350^{\circ}\text{C}$). The hydrothermal process studied uses a homogeneous potassium carbonate catalyst, a fixed-bed zirconia catalyst, and recirculation of the reaction mixture.

Otero et al studied the anaerobic digestion of cattle biomass was studied under thermophilic and mesophilic conditions with the purpose of evaluating the effect of temperature on the quality of the final digestate. Non-isothermal thermo gravimetric kinetic analysis was applied for assessing organic matter conversion of biological stabilization. The carrier gas was Helium and the columns were operated at 331 kPa and a temperature of 50°C . Volatile fatty acids (VFA) were analyzed using a gas chromatograph (Varian CP 3800 GC) equipped with a capillary column Nukol, 30 m - 0.25 mm - 0.25 μm film (from Supelco) and a Flame ionization detector. The carrier gas was Helium and the temperature of the injector was

250°C. The temperature of the oven was set at 150°C during 3 min followed by an increase to 180°C. A temperature range of 52–56°C for practical operation of full scale plants, reporting a 37% increase when operation was performed at 55°C instead of using the “reduced” thermophilic range (47°C). Higher values of methane yield reported for the mesophilic digestion were in accordance with the lower values of the activation energy obtained and thus indicated a higher conversion of organic matter.

Toor et al studied about bio-refinery concepts which are currently receiving much attention due to the drive toward flexible, highly efficient systems for utilization of biomass for food, feed, fuel and biochemicals. The catalytic liquefaction process is carried out at sub-critical conditions (280-370°C and 25 MPa) in the presence of a homogeneous alkaline and a heterogeneous Zirconia catalyst, a process known as the Catliq process. Pyrolysis is the process of thermochemical transformation of biomass under non-oxidative conditions. Typical fast pyrolysis conditions are 500-520°C and residence time of 1-5 s. Most of the processes operate at pressures and temperatures in the range of 250-350 °C and 10-25 MPa respectively. In the CatLiq process the organic fraction of the feed stream is converted to oil in the presence of a homogeneous (K_2CO_3) and a heterogeneous (Zirconia-based) catalyst, at subcritical conditions (280-370°C and 25 MPa). K_2CO_3 (homogeneous catalyst) corresponding to wB $\frac{1}{4}$ 2.5% was added. The heterogeneous catalyst in the reactor was zirconia (ZrO_2). The oil is used directly for substitution of fossil fuels in combustion applications for production of green heat and power, in larger diesel engines such as marine engines, or may be used as a green feedstock for further upgrading to transportation fuel.

Hoffmann et al studied that in a biogas plant, organic materials, such as animal biomass, energy crops or industrial organic sludge, are anaerobically digested to produce biogas in

airtight reactors. Through this decomposition, organic bound carbon in the biomass slurry is converted primarily into a mixture of CH_4 and CO_2 . Two operation modes are used: mesophilic and thermophilic digestion. Mesophilic plants digest at 35–40 °C, and thermophilic plants operate at 50–60 °C. In Aspen Plus, the Soave-Redlich-Kwong (SRK) cubic equation of state for all thermodynamic properties is used for the simulation. The biomass input and the digestate are modeled as non-conventional solids using two special models named HCOALGEN and DCOALIGT. These models are designed for coal-derived materials. HCOALGEN models the enthalpy of the biomass and digestate, whereas DCOALIGT is used to model the density of the components. HCOALGEN requires input of the ultimate, proximate and sulphate analysis of the component. To upgrade the biocrude, hydrogen needs to be produced from part of the biogas stream. To keep the process sustainable, hydrogen for the upgrading process is made available through steam reforming of biogas, which is fed to the upgrading unit of the plant. The end-product biofuel from the model is a mixture containing conventional diesel fuel components: benzene, cyclohexanone, cyclohexane, hexadecane and pentadecane

PROCESS DESCRIPTION

The integrated process that is designed is based on the concept of both the Hydrothermal Liquefaction unit and the Biogas Plant unit. The main input is the digestate that consists of organic materials such as animal biomass, energy crops or industrial organic sludge ^[4]. The input is feed into the biogas plant. It is anaerobically digested to produce biogas in airtight reactors. The output of the biogas plant unit is feed into the HTL unit. Then the output of the HTL unit is treated in order to upgrade the output in upgrading unit. And also the hydrogen producing unit is used for the methane recovery and the methane steam recovery process. A portion of the biogas from the digestion process is sent to the upgrading facility and is used in a CPH unit before eventually going to a gas boiler. The ultimate output from the integrated design is the bio crude and wastewater. The waste water is further used for the purpose fertilizers.

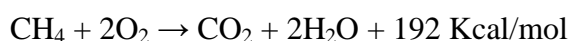
There are four major parts in the integrated design of the plant. The design consists of a Biogas plant unit, Hydrothermal Liquefaction unit, an Upgrading unit and a Hydrogen Producing unit. The model compounds are described below:

3.1 BIOGAS PLANT

Biogas ^[16] typically refers to a gas produced by the breakdown of matter in absence of oxygen. Biogas is a renewable energy source, like solar energy and wind energy. Biogas is produced by the anaerobic or fermentation of biodegradable materials such as biomass, sewage, plant material, municipal waste, green waste and crops. The gases methane, hydrogen, and carbon monoxide (CO) can be combusted or oxidized with oxygen. The energy released allows biogas to be used as a fuel ^[6]. Biogas can be utilized for electricity production on sewage works in the CHP gas engine unit, where the waste heat from the engine is conveniently used for heating the digester; cooking; space heating; water; and process heating. Methane within biogas can be concentrated via a biogas upgrader to the same standards as fossil natural gas which itself has to go through a cleaning process, and becomes bio methane.

The biogas components ^[11] which are contained in its gaseous mixture are those that make it capable for producing renewable energy. During anaerobic digestion of organic materials which contain certain groups of anaerobic bacteria, the organic component is converted into biogas, a gaseous combustible mixture, which has the ability to be used in various applications for energy production ^[11].

The main compound consisted in biogas mixture is methane (CH₄) which is actually the compound that produces biogas and some of its combustible properties. Methane is easily burned according to the following well-known exothermic combustion equation ^[11]:



Carbon dioxide is removed from biogas only when the target is to upgrade it into bio methane as a product. In conventional biogas CHP plants the equipment for capturing CO₂ is not required.

The amount of biogas obtained from the biomass feed depends on several factors: the dry matter content of the slurry, the origin of the slurry and the conditions and reaction time in

the digester. The biogas or methane digestion involves fermentation anaerobic (without air) residues and various organic materials (cattle dung, pig, human faces, etc.). This fermentation leads to the formation of a methane-rich gas called biogas. This energy source is directly used for powering appliances such as refrigerators, burners, gas lamps, or to generate electricity through a generator ^[12]. The bioconversion is carried out in sealed vats called digesters. A portion of the biogas from the digestion process is sent to the upgrading facility and is used in a CPH unit before eventually going to a gas boiler.

3.2 HYDROTHERMAL LIQUEFACTION UNIT

Hydrothermal Liquefaction (HTL) ^{[3][4]} also called hydrous pyrolysis is a process for the reduction of complex organic materials such as bio - waste or biomass into crude oil and few other chemicals. It mimics the natural geological processes thought to be involved in the production of fossil fuels. HTL is one of the processes of a general term of TCC which includes gasification, liquefaction, HTL, and pyrolysis. There is a general consensus that all fossil fuels found in nature — petroleum, natural gas, and coal, based on biogenic hypothesis — are formed through processes of TCC from biomass buried beneath the ground and subjected to millions of years of high temperature and pressure. Gasification of biomass produces a mixture of hydrogen and carbon monoxide, commonly called syngas. It is then reformed into liquid oil with the presence of a catalyst. Pyrolysis is a heating process in which dried biomass directly produce syngas and oil. Both gasification and pyrolysis need dried biomass as feedstock and the processes takes place in an environment higher than 600°C. HTL involves direct liquefaction of biomass, in presence of water and perhaps some catalysts which directly converts biomass into liquid oil, and a reacting temperature of less than 400°C.

HTL has different pathways for the biomass feedstock. Unlike biological treatment like anaerobic digestion, HTL converts feedstock into oil. There are some unique characteristics

of the HTL process and its product compared with other biological processes. First, the end product is the crude oil which has much higher energy content than syngas or alcohol. And second, if feedstock contains a lot of water, HTL does not require drying as gasification or pyrolysis. The drying process primitively takes large quantities of energy and time. The energy is used to heat up the feedstock in the HTL process could be recovered effectively with the existing technology ^[8].

The chemistry of hydrothermal liquefaction is complicated and highly substrate dependant and will be addressed in the following sections. The main products are bio crude with a relatively high heating value, char, water-soluble substances and gas. Addition of various alkaline catalysts can suppress char formation and thus improve oil yield and quality. In addition to hydrothermal liquefaction, a range of other hydrothermal conversion processes exist, however they are usually carried out at higher temperatures. Hydrothermal liquefaction processes have the potential to become an important group of technologies for converting wet biomass or organic waste into bio-oil for fuel or other applications. The hydrothermal liquefaction process holds significant potential, particularly for producing specific fuels targeted for the heavy transport sector, combustion purposes, and as a raw material for further chemical processing.

Water plays an essential role in HTL. Water is rather being and will not likely react with organic molecules under standard environmental conditions (20°C and 101,325 kPa). However, when the temperature increases rapidly, two properties of water molecules change substantially. First, the relative permittivity (dielectric constant), ϵ_r , of water decreases quickly when the temperature increases. When the thermal energy increases, the electron shared by oxygen and hydrogen atoms tends to circulate more evenly and the electronegativity of the oxygen molecule is reduced (less polar).

Second, the dissociation of water dramatically increases with the increase of temperature. Water, like any other aqueous solutions, split into H^+ and OH^- ions in hydrolysis or dissociation. This process is reversible and the rate is sufficiently rapid so it can be considered to be in equilibrium at any instant ^[8].

3.3 HYDROGEN PRODUCING UNIT

To upgrade the biocrude, hydrogen needs to be produced from part of the biogas stream. Thus, the biogas components are separated using a membrane separator. A membrane module described for biogas separation results in a recovery of 99% CH_4 ^[4]. This setup consists of a recycle process, two membrane units with different feed pressures and several compressors and heat exchangers. However, the membrane module in this simulation is simplified to consist of one multistage compression series and one membrane unit.

The pre-treated feed gas (CH_4) is mixed with steam before entering the reforming reactor. The steam methane reforming (SMR) reaction is highly endothermic and catalyzed by nickel. Excess steam is added to prevent coke formation in the reactor tank. In the reactor tank, the gas mixture is channeled through nickel catalysts.

3.4 UPGRADING UNIT

Oxygen atoms can be removed from the carboxylic group of hexadecanoic acid in the form of water by Hydrodeoxygenation. In the hydrodecarbonylation reaction, oxygen can be eliminated as CO and water. Hydrodecarboxylation leads to the elimination of a carboxylic group in the form of carbon dioxide. To keep the process sustainable, hydrogen for the upgrading process is made available through steam reforming of biogas, which is fed to the upgrading unit of the plant. The end-product biofuel from the model is a mixture containing conventional diesel fuel components: benzene, cyclohexanone, cyclohexane, hexadecane and pentadecane ^[4].

The relationship between the cooling and heating utilities illustrates the high potential for process integration and the need for further development of a heat recovery system. Pending this development, the evaluation of the plant is based on the electricity needs for pumps and compressors as modeled. These utilities are covered by burning the remaining biogas (i.e., that which is not used for biocrude upgrading) partially or completely in a CHP unit ^[4], releasing heat that is supplemented by burning the off gas from the HP and upgrading unit in a gas boiler. Plant design offers possible solutions for and simplification of the issues of existing biogas plants. Because the digestate is directly converted after production in the biogas plant, no large storage tanks are necessary. Analysis of the waste water from the hydrothermal liquefaction processes has not been available other than with respect to the contents of fatty acids and alcohols. Depending on the concentration of the nutrients like to nitrogen, phosphor and potassium it might be more cost-effective to either extract the nutrients and sell them as solids or pass on the waste water as an untreated liquid.

Hydrogen could be produced by electrolysis using renewable electricity from wind or solar. This would help to reduce the impact of fluctuating sources of electricity on the electric grid. But also recycling the remaining hydrogen in the off gas stream from the HPU and upgrading unit instead of burning it in a gas boiler would higher the sustainability of the plant. Because all calculations are based on model components, it would be of great interest to further characterize biocrude from HTL and biofuel from upgrading in future studies and to develop a more precise model composition of biomass, biocrude and biofuel ^[4].

3.5 OVERALL STEPS OF THE PROCESS

1. The biomass is circulated among the four units namely biogas plant, hydrothermal liquefaction unit, upgrading unit and hydrogen producing unit. The ultimate product is obtained from the hydrothermal liquefaction unit after being processed in biogas plant that produces biogas as a by-product. Waste water is obtained along with the product. This waste water can be further used as fertilizers.
2. In a biogas plant, organic materials, such as animal biomass, energy crops or industrial organic sludge, are anaerobically digested to produce biogas in airtight reactors. Through this decomposition, organic bound carbon in the biomass slurry is converted primarily into a mixture of CH_4 and CO_2 . Two operation modes are used: mesophilic and thermophilic digestion. Mesophilic plants digest at 35–40°C, and thermophilic plants operate at 50–60°C ^[4].
3. The digestate obtained from anaerobic digestion is further converted using hydrothermal liquefaction. During hydrothermal liquefaction (HTL), wet biomass feedstock is converted at medium temperatures and pressures (280–360°C, 180–300 bar) into a liquid biomass fuel, referred to as bio crude hereafter ^[4].
4. The digestate is at first feed into the biogas plant, where upon the action of catalysts, the digestate is broken down into smaller particles. This digestion is anaerobic in nature. The major product obtained from the plant is biogas which is a composition of CH_4 and CO_2 . The methane gas is used for various purposes. The other product i.e. the bio crude obtained from the plant is then allowed to get processed in HTL unit.
5. The products of biogas plant are feed into the HTL unit for processing. HTL involves direct liquefaction of biomass, in presence of water and perhaps some catalysts which directly converts biomass into liquid oil, and a reacting temperature of less than 400° C. HTL converts feedstock into oil. Water plays an essential role in HTL.

6. By-products of the HTL process are a solid fraction containing nutrients, minerals and metals; a water fraction containing low amounts of soluble organics; and a gas fraction, mostly consisting of CO₂ ^[4].
7. The higher oxygen content in the bio crude leads to undesirable properties. The properties that most negatively affect bio crude quality are incompatibility with conventional fuels low heating value, solids content, incomplete volatility, high viscosity and chemical instability.
8. The gas products from the biogas plant (mainly CO₂ and CH₄) can be used to generate heat and electricity for the plant, upgraded and fed to the gas grid or steam-reformed to H₂ and used for further hydro treating of the bio crude for conversion into diesel quality fuel.
9. Offgas from the steam reforming and upgrading units can also be used for internal heat and the power supply. Waste water from the hydrothermal liquefaction unit, can be used for fertilizer purposes and integrated to the heat recovery network of the plant.
10. Hydrogen production unit is used to upgrade the bio crude and hydrogen needs to be produced from part of the biogas stream. Two membrane units with different feed pressures and several compressors and heat exchangers are used for this recycle process.
11. The upgrading unit is used to keep the process sustainable and hydrogen for the upgrading process is made available through steam reforming of biogas which is fed to the upgrading unit.
12. The end-product biofuel from the model is a mixture containing conventional diesel fuel components: benzene, cyclohexanone, cyclohexane, hexadecane and pentadecane.

ASPEN PLUS SIMULATION

The simulation of the integrated design of the plant is done using Aspen Plus 11.1. A steady state system has been modelled to provide an initial model without the potentially complex considerations of dynamics. The process simulation was performed with operating conditions based on data from the literature. In Aspen Plus, the Soave-Redlich-Kwong (SRK) cubic equation of state for all thermodynamic properties is used for the simulation. Initially the simulation starts with the biomass conversion process, the overall process is divided into four independent sections: anaerobic biomass digestion (biogas plant), hydrogen production, hydrothermal liquefaction and upgrading of the biocrude. The biomass input and the digestate are modeled as non-conventional solids.

There are two special models namely the HCOALGEN and DCOALIGT that are being used for the coal derived materials which are the being used in biomass. HCOALGEN models the enthalpy of the biomass and digestate and DCOALIGT is used to model the density of the components. The HCOALGEN model includes a number of different correlations. The heat of combustion, the heat of formation and the heat capacity, the Boie correlation, a heat-of-combustion-based correlation and the Kirov correlation are used, respectively, based on the entered elemental attributes of the components. The standard conditions are assumed to be temperature of 298.15K and pressure of 1 atm ^[4]. The DCOALIGT model uses ultimate and sultanate analysis. Aspen Plus calculates energy and mass balances for the complete process of converting biomass to biofuel.

The lower heating value (LHV) of the substrate biomass and digestate is calculated in the ultimate analysis by using the Boie correlation:

$$\text{LHV}_{\text{Boie}} = 34.8C + 93.9H_2 + 6.3N_2 + 10.5S - 10.8O_2 - 2.44H_2O$$

4.1 BIOGAS PLANT UNIT SIMULATION

The amount of biogas obtained from the biomass feed depends on several factors: the dry matter content of the slurry, the origin of the slurry and the conditions and reaction time in the digester. For this model, the input to the biogas plant is assumed to be 1000 kg h^{-1} . The digestion process used in this study works under thermophilic conditions; thus, a digester temperature of 51°C is used in the simulation ^[4]. The yield of biogas is obtained from the laboratory (Oetro et al.) and has a low yield of biogas: $0.26 \text{ m}^3\text{kg}^{-1} \text{ VS}$.

The biogas is modeled as 62 vol.% CH_4 and 38 vol.% CO_2 ^[4]. For both simulations, biomasses with the same proximate and ultimate analyses and DM content in their substrates are used. The digester is modeled as a RYield reactor in Aspen Plus. It is assumed that no water vaporizes during the digestion process. The ASPEN Flowsheet for the Biogas plant unit is being described in the Fig.2.

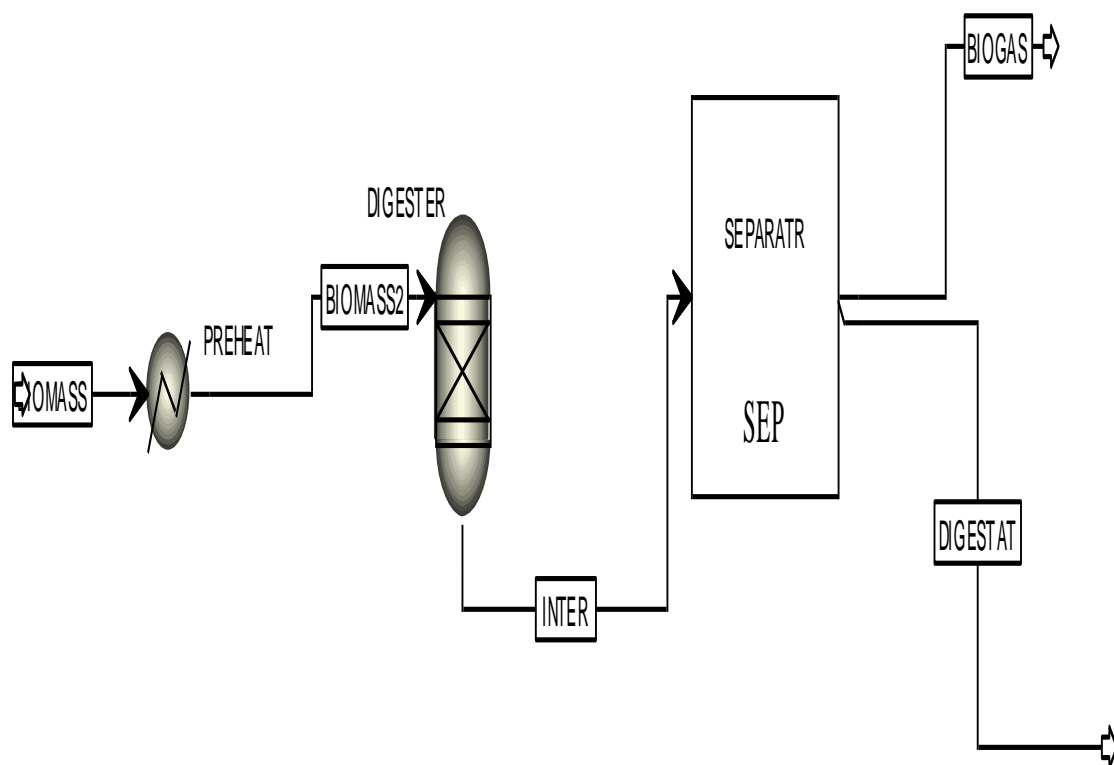


FIGURE 2: FLOWSHEET OF BIOGAS PLANT UNIT

TABLE 1: PROXIMATE ANALYSIS OF DIGESTATE (IN %)

Name of compound	Fresh biomass	Thermophilic Digestate
Volatiles	62.3	55.5
Fixed Carbon	17	18.8
Ash	20.7	25.7
Water content	7	6.8

TABLE 2: ULTIMATE ANALYSIS OF DIGESTATE (IN %)

Name of compound	Fresh biomass	Thermophilic Digestate
Carbon (C)	37.9	35.8
Hydrogen (H)	10.1	9.5
Nitrogen	3	3.2
Sulphur (S)	0.3	0.3
Oxygen (O)	28	25.5

The biomass utilized in the biogas plant is cattle biomass plus bedding material with a total dry matter (DM) content of 17.2 wt.%. The total DM of the biomass consists of 82.7 wt.% volatile solids (VS). A portion of the biogas from the digestion process is sent to the upgrading facility and is used in a CPH unit before eventually going to a gas boiler. The electrical efficiency of the CHP unit is assumed to be 39%. The thermal efficiency is assumed to be 52%, and the thermal efficiency of the gas boiler is set at 98% ^[4].

4.2 HYDROTHERMAL LIQUEFACTION UNIT SIMULATION

A temperature of 330°C and pressure of 250 bars are the converting conditions in the HTL reactor ^[4]. It is therefore assumed that exothermic and endothermic reactions are balanced during the biomass to biocrude conversion which is described in Fig 3. It is assumed that exothermic and endothermic reactions are balanced during the biomass to biocrude conversion. The designed Aspen flowsheet is shown in Fig. 3. The recycle loop is neglected in these preliminary process studies, but using a recycle loop would be expected to lower the heating duties.

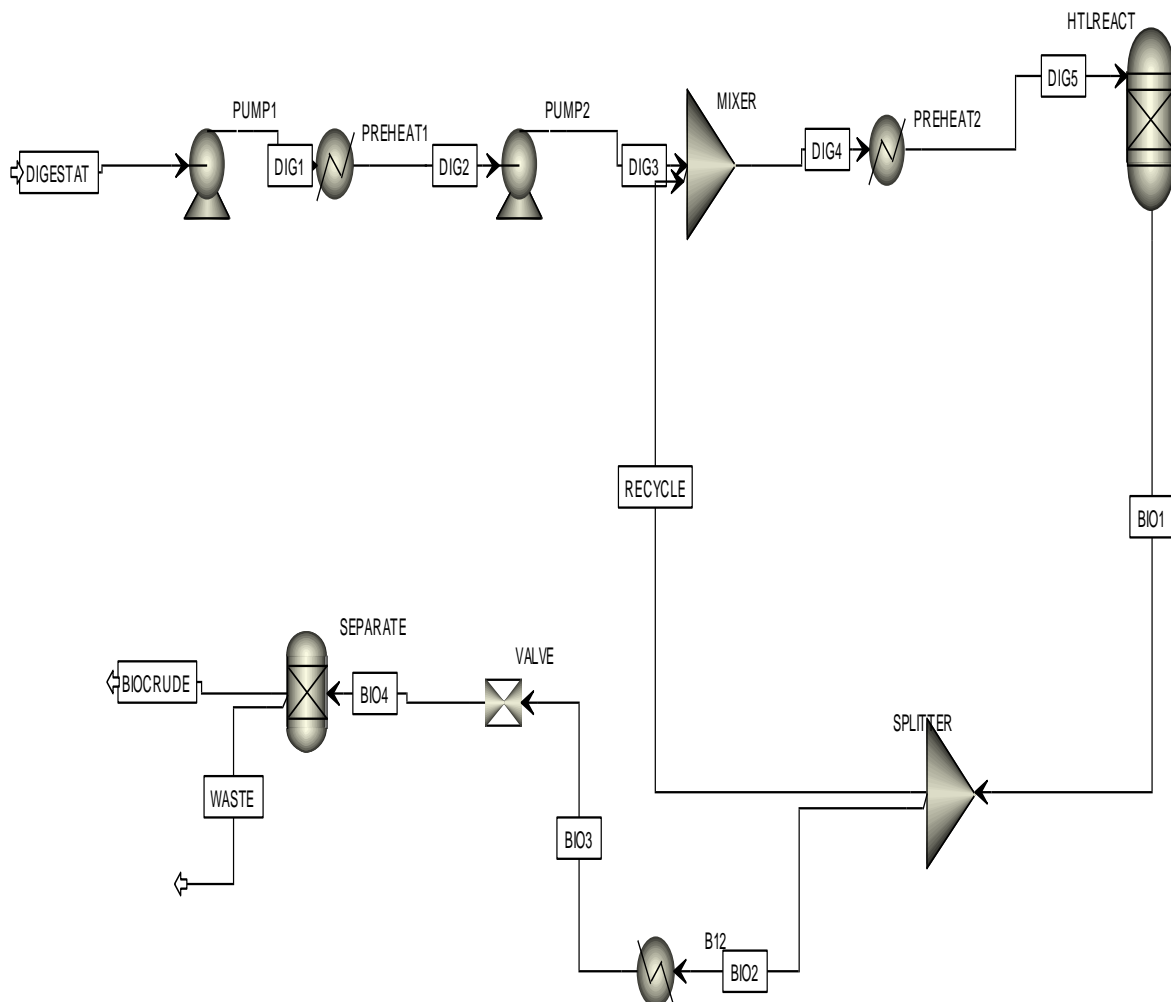


FIGURE 3: FLOWSHEET OF HTL UNIT

4.3 HYDROGEN PRODUCING UNIT SIMULATION

In order to upgrade the biocrude of the input, hydrogen needs to be produced from part of the biogas stream. Thus the biogas components are separated using a membrane separator. Here the RGibbs Aspen Plus reactor models are used. Two membrane units along with different feed pressures and several compressors and heat exchangers are present in the design described in Fig 4. The pre-treated feed gas (CH_4) is mixed with steam before entering the reforming reactor. The ratio of $\eta_{\text{water}}/\eta_{\text{methane}}$ is set to 1.5 ^[4].

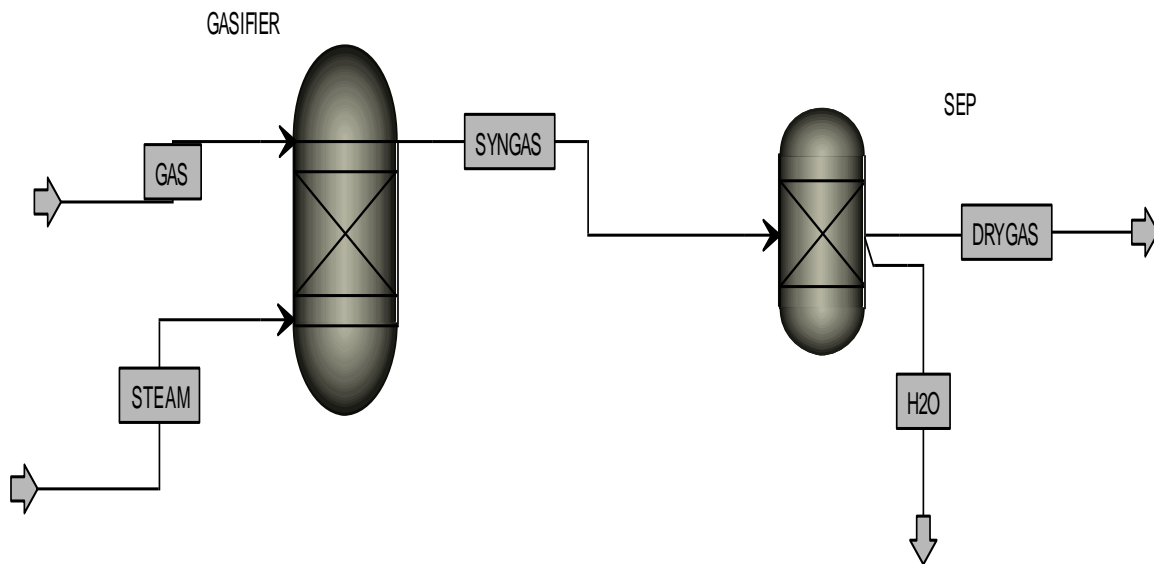
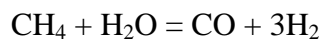
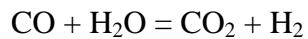


FIGURE 4: FLOW SHEET OF HYDROGEN PRODUCTION UNIT

The temperature inside the reactor varies from to 750 to 850°C.

The reactions involved in the production of hydrogen are mentioned below:



4.4 UPGRADING UNIT SIMULATION

In order to keep the process sustainable, hydrogen for the upgrading process is made available through steam reforming of biogas which is fed to the upgrading unit of plant. And Rstoisic Aspen Plus reactor model is used. Hydrogen and biocrude are being compressed to 80 bar and heated to 80°C mixed and sent to the upgrading reactor ^[4] described in the flowsheet in Fig 5.

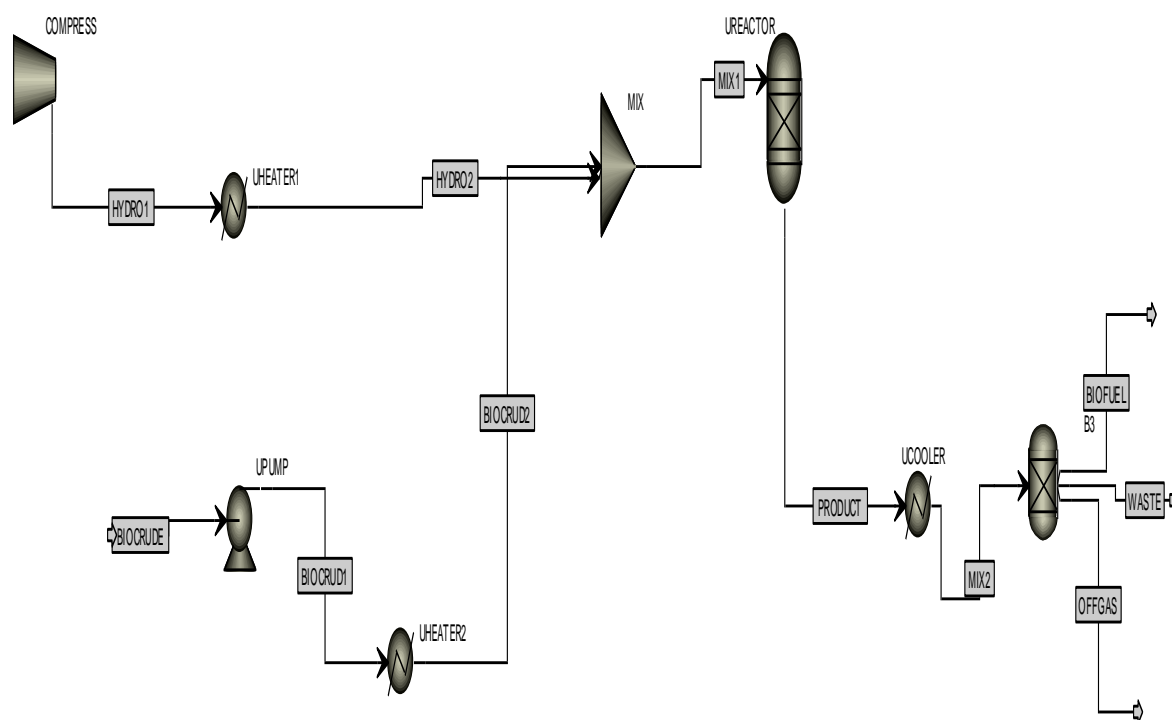


FIGURE 5: UPGRADING UNIT

The different reactions involved in the unit are mentioned below adapted from (Ahmad et al.):

Phenol

Phenols→Benzene: $C_6H_5(OH) + H_2 \rightarrow C_6H_6 + H_2O$ (conversion 34%)

Phenols→Cyclohexanone: $C_6H_5(OH) + 2 H_2 \rightarrow C_6H_{10}O$ (conversion 34%)

Cyclohexanone→Cyclohexanol: $C_6H_{10}O + H_2 \rightarrow C_6H_{11}(OH)$ (conversion 100%)

Cyclohexanol→Cyclohexene: $C_6H_{11}(OH) \rightarrow C_6H_{10} + H_2O$ (conversion 100%)

Cyclohexene→Cyclohexane: $C_6H_{10} + H_2 \rightarrow C_6H_{12}$

Hexadecanoic acid

n-Hexadecanoic acid→n-Hexadecane $C_{16}H_{32}O_2 + 3 H_2 \rightarrow C_{16}H_{32} + 2 H_2O$ (conversion 80%)

n-Hexadecanoic acid→n-Pentadecane $C_{16}H_{32}O_2 + H_2 \rightarrow C_{15}H_{32} + CO + H_2O$ (conversion 10%)

n-Hexadecanoic acid→n-Pentadecane $C_{16}H_{32}O_2 \rightarrow C_{15}H_{32} + CO_2$ (conversion 10%)

The end-product biofuel from the model is a mixture containing conventional diesel fuel components: phenol, benzene, cyclohexanone, cyclohexane, hexadecane and pentadecane.

The evaluation of the plant is based on the electricity needs for pumps and compressors as modeled. These utilities are covered by burning the remaining biogas (i.e., that which is not used for biocrude upgrading) partially or completely in a CHP unit, releasing heat that is supplemented by burning the offgas from the HP and upgrading unit in a gas boiler.

RESULTS

TABLE 3: BIOGAS PLANT SIMULATION (T= 298.15K, P=1atm)

Stream ID		BIOGAS	BIOMASS	BIOMASS2	DIGESTAT	INTER
Temperature	K	324.1				324.1
Pressure	atm	1.000	1.000	1.000	1.000	1.000
Vapor Frac		1.000				1.000
Mole Flow	Kmol/hr	1.791	0.000	0.000	0.000	1.791
Mass Flow	Kg/hr	37.880	0.000	0.000	0.000	37.880
Volume Flow	l/min	792.691	0.000	0.000	0.000	792.691
Enthalpy	MMkcal/hr	-0.056				-0.056
Mole Flow	Kmd/hr					
METHA-01		1.464				1.464
CARBO-01		0.327				0.327
Mass Flow	Kg/hr		1000.000	1000.000	962.120	1000.000
Enthalpy	MMkcal/hr	-0.056	-1.384	-1.384	0.000	-0.056
Temperature	K		298.1	298.1	324.1	324.1
Pressure	atm	1.000	1.000	1.000	1.000	1.000
Vapor Frac			0.000	0.000	0.000	0.000
Mass Flow	Kg/hr	0.000	1000.000	1000.000	962.120	962.120
Enthalpy	MMkcal/hr		-1.384	-1.384	0.000	0.000
Mass Flow	Kg/hr					
BIOMASS			1000.000	1000.000		
DIGESTAT					962.120	962.120

TABLE 4: HTL UNIT SIMULATION (T=330°C, P=250 bar)

	BIO1	BIO2	BIO3	BIO4	BIO-CRUDE	DIG1	DIG2	DIG3	DIG4	DIG5	DIGESTAT	RECYCLE	WASTE
Temperature K	603.15	603.15	298.15	298.15	298.15				384.5	473.15		603.1	298.2
Pressure atm	246.73	246.73	1	0.1	0.1	3	1	3	1	1	3.402	24.73	0.1
Vapor Frac	0	0	0	0	0				0	0.862		0	0
Mole Flow kmol/hr	9.676	8.709	8.709	8.709	0.313	0	0	0	0.968	0.968	0	0.968	8.396
Mass Flow kg/hr	1042.6	938.4	938.4	938.4	33.73	0	0	0	104.26	104.26	0	104.26	904.67
Volume Flow l/min	21.74	19.57	14.857	14.857	0.534	0	0	0	1.765	528.97	0	2.174	14.324
Enthalpy MMBtu/hr	-1.21	-1.089	-1.72	-1.72	-0.062				-0.174	-0.12		-0.121	-1.659
Mole Flow kmol/hr													
PHENO-01	8.863	7.977	7.977	7.977	0.287	0	0	0	0.886	0.886	0	0.886	7.69
N-HEX-01	0.813	0.732	0.732	0.732	0.026	0	0	0	0.081	0.081	0	0.081	0.706
Mass Flow kg/hr	1042.6	938.4	938.4	938.4	33.73	938.4	938.4	938.4	1042.6	1042.6	938.4	1042.6	904.67
Enthalpy MMBtu/hr	-1.21	-1.089	-1.72	-1.72	-0.062	-4.78	-4.74	-4.74	-4.863	-4.661	-4.781	-0.121	-1.659
Temperature							350		384.5	473.1	324.1		
Pressure atm	246.73	246.73	1	0.1	0.1	3	1	3	1	1	3.402		0.1
Vapor Frac							0		0	0	0		
Mass Flow kg/hr	0	0	0	0	0	938.4	938.4	938.4	938.4	938.4	938.4	0	0
Enthalpy MMBtu/hr						-4.78	-4.74	-4.74	-4.689	-4.541	-4.781		
Mass Flow kg/hr													
DIGESTAT				0	0	938.4	938.4	938.4	938.4	938.4	938.4		
WASTE										0	0		

TABLE 5: ENTHALPY VS RECYCLE FOR HTL UNIT

Recycle	Enthalpy(MJ/hr)
0	1177.717
0.1	1308.57
0.2	1472.146
0.3	1682.453
0.4	1962.86
0.5	2355.43

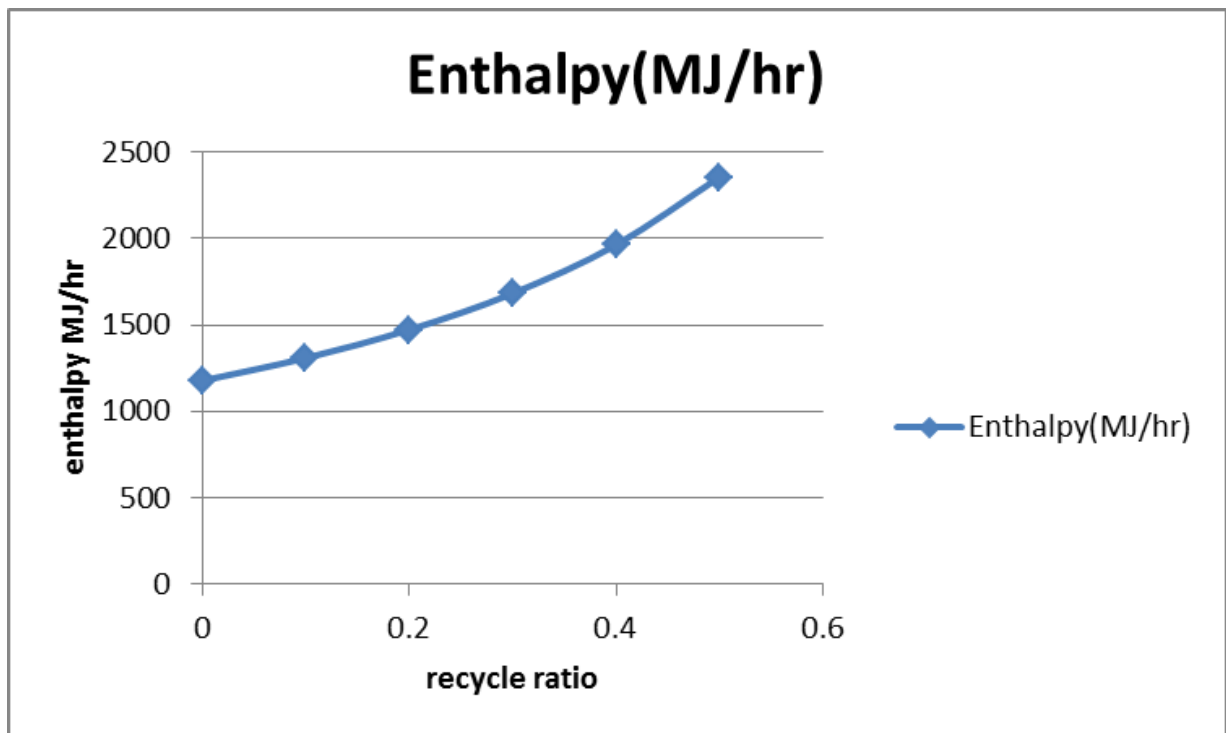


FIGURE 6: GRAPH REPRESENTING ENTHALPY VS RECYCLE

TABLE 6: HYDROGEN PRODUCTION UNIT SIMULATION (T=700°C, P=1atm)

	DRYGAS	GAS	H2O	STEAM	SYNGAS
Temperature K	973.1	324.1	973.1	673.1	973.15
Pressure atm	10	1	10	1	10
Vapor Frac	1	1	1	1	1
Mole Flow kmol/hr	3.018	1.458	0.924	1.528	3.943
Mass Flow kg/hr	40.23	29.36	16.655	27.525	56.885
Volume Flow l/min	402.725	645.335	122.652	1404.621	525.376
Enthalpy MMkcal/hr	-0.036	-0.042	-0.048	-0.083	-0.084
Mole Flow Kmol/hr					
HYDRO-01	1.56				1.56
METHA-01	0.766	1.244			0.766
CARBO-01	0.353	0			0.353
CARBO-02	0.338	0.213			0.338
WATER			0.924	1.528	0.924

TABLE 7: GAS COMPOSITION VS TEMPERATURE FOR HPU UNIT

Temperature	600	650	700	750	800	850	900
HYDROGEN	58.853	64.438	68.041	69.863	70.527	70.693	70.693
METHANE	16.309	8.94	4.053	1.501	0.5006	0.165	0.066
CO	12.674	18.04	22.005	24.266	25.433	26.053	26.485
CO ₂	12.162	8.578	5.899	4.368	3.538	3.086	2.754

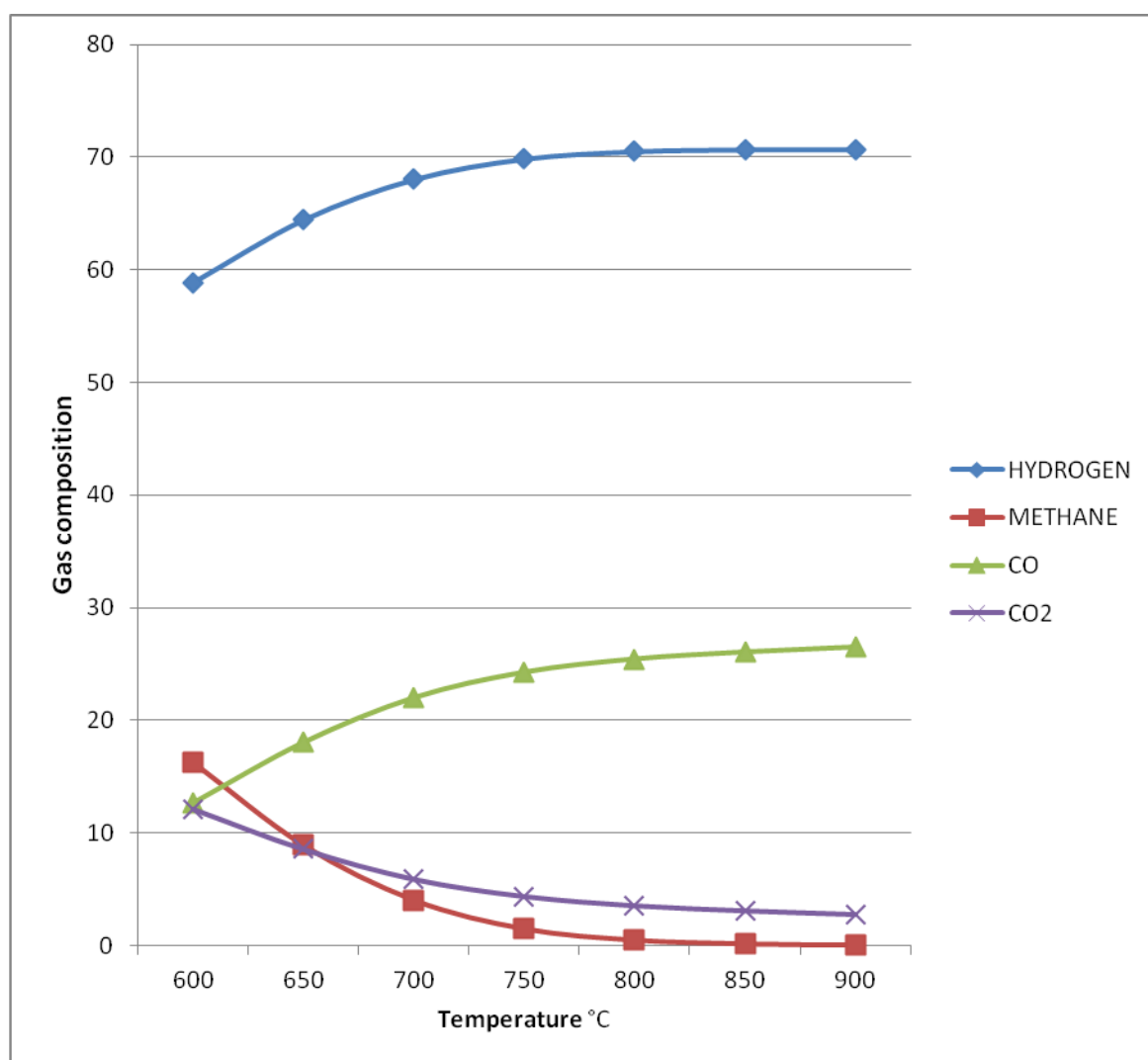


FIGURE 7: GRAPH REPRESENTING GAS COMPOSITION VS TEMPERATURE

TABLE 8: CO/CO₂ VS TEMPERATURE FOR HPU UNIT

Temperature	600	650	700	750	800	850	900
CO/ CO ₂	1.042	2.103	3.73	5.555	7.188	8.442	9.6169

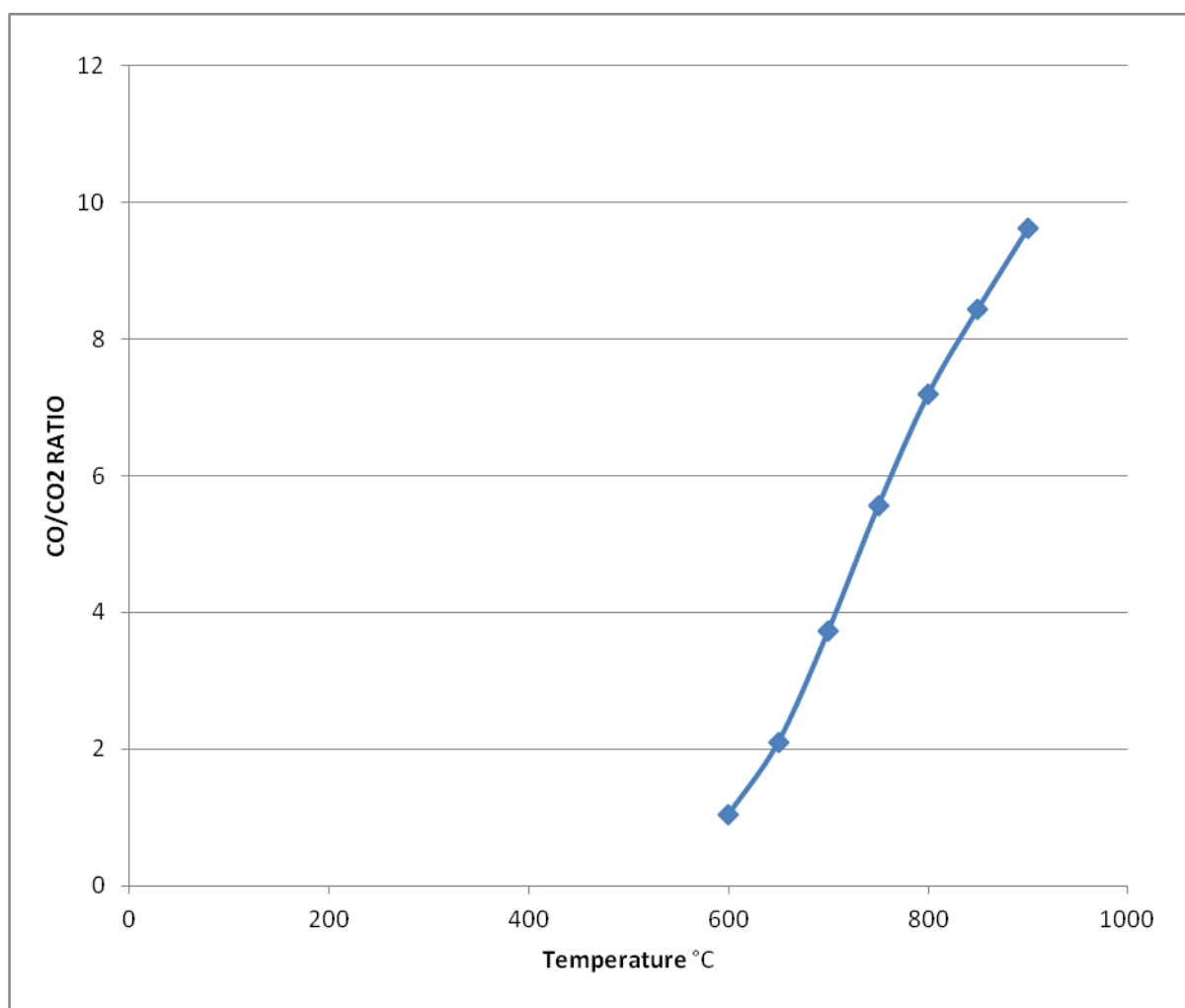


FIGURE 8: GRAPH REPRESENTING CO/CO₂ VS TEMPERATURE

TABLE 9: GAS COMPOSITION VS PRESSURE FOR HPU UNIT

Pressure	1	2	3	4	5	6	7	8	9	10
HYDROGEN	68.041	64.597	61.912	59.772	57.952	56.345	54.994	53.745	52.654	51.642
METHANE	4.053	8.37	11.719	14.396	16.619	18.567	20.234	21.739	23.056	24.26
CO	22.005	19.503	17.707	16.355	15.285	14.419	13.659	13.043	12.493	12.048
CO ₂	5.899	7.529	8.66	9.476	10.142	10.666	11.111	11.471	11.796	12.048

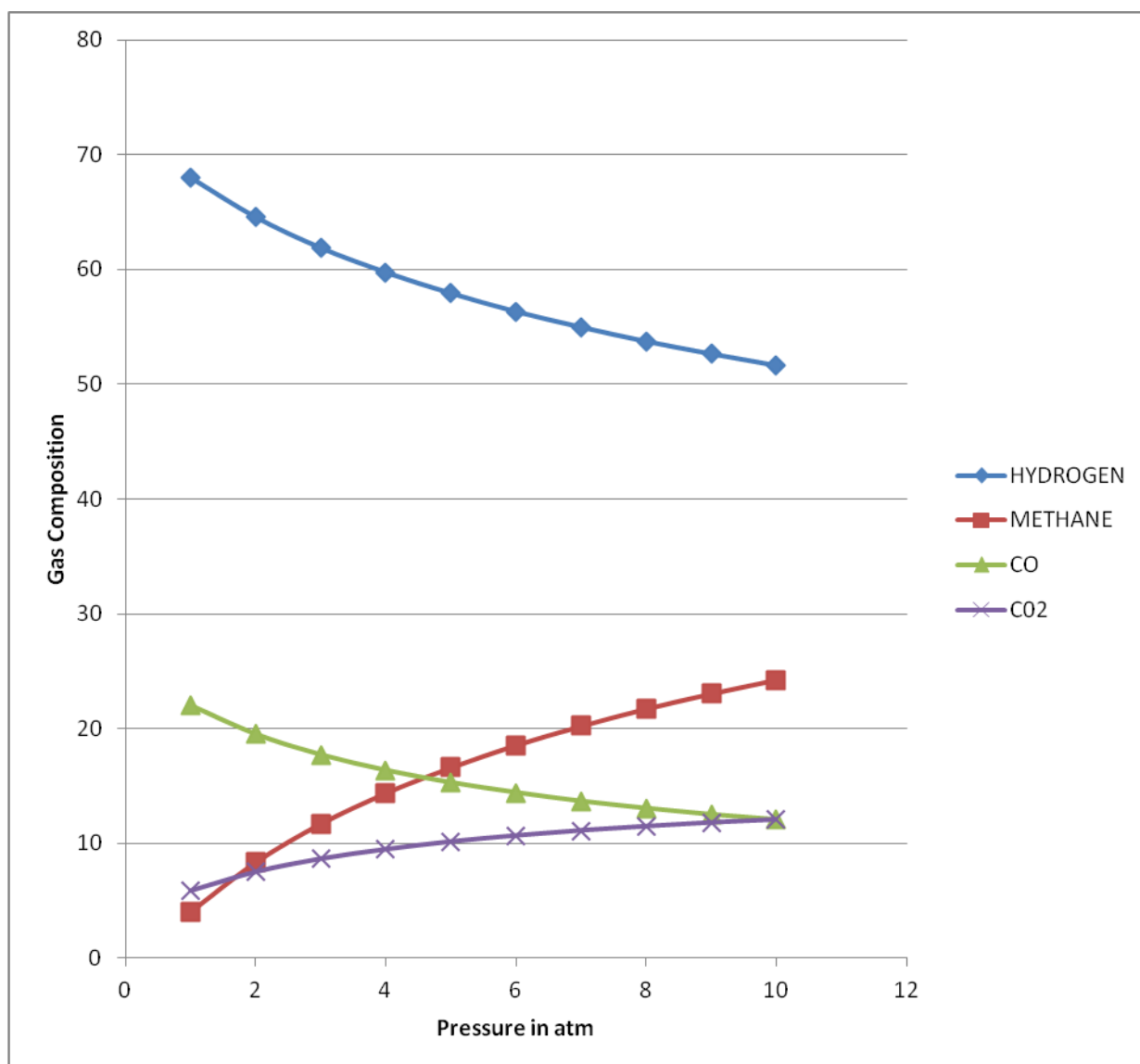


FIGURE 9: GRAPH REPRESENTING GAS COMPOSITION VS PRESSURE

TABLE 10: UPGRADING UNIT SIMULATION (T=300°C, P=80 bar)

simulation 4													
Stream ID		2	BIOCRUD1	BIOCRUD2	BIOCRUDE	BIOFUEL	H2	HYDRO1	HYDRO2	MIX1	MIX2	OFFGAS	WASTE
From		UREACTOR	UPUMP	UHEATER2		B3		COMPRESS	UHEATER1	MIX	UCCOOLER	B3	B3
To		UCCOOLER	UHEATER2	MIX	UPUMP		COMPRESS	UHEATER1	MIX	UREACTOR	B3		
Phase		MIXED	LIQUID	LIQUID	LIQUID	LIQUID	VAPOR	VAPOR	VAPOR	MIXED	MIXED	VAPOR	MIXED
Substream: MIXED													
MoleFlow	kmol/hr												
HYDRO-01		6044779	00	00	00	00	6095601	6095601	6095601	6095601	6044779	6044779	00
PHENO-01		.1516659	.3481770	.3481770	.3481770	.1516659	00	00	00	.3481770	.1516659	00	00
N-HEX-01		5.17533E-3	.0319464	.0319464	.0319464	00	00	00	00	.0319464	5.17533E-3	00	5.17533E-3
BENZE-01		.1183802	00	00	00	.1183802	00	00	00	00	.1183802	00	00
CYCLO-01		00	00	00	00	00	00	00	00	00	00	00	00
CYCLO-02		.0781309	00	00	00	.0781309	00	00	00	00	.0781309	00	00
N-HEX-02		.0255571	00	00	00	.0255571	00	00	00	00	.0255571	00	00
N-PEN-01		1.21397E-3	00	00	00	1.21397E-3	00	00	00	00	1.21397E-3	00	00
CYCLO-03		00	00	00	00	00	00	00	00	00	00	00	00
CYCLO-04		00	00	00	00	00	00	00	00	00	00	00	00
WATER		.2482644	00	00	00	00	00	00	00	00	.2482644	00	.2482644
CARBO-01		6.38930E-4	00	00	00	00	00	00	00	00	6.38930E-4	6.38930E-4	00
CARBO-02		5.75037E-4	00	00	00	00	00	00	00	00	5.75037E-4	5.75037E-4	00
MoleFrac													
HYDRO-01		.9896917	00	00	00	00	1.000000	1.000000	1.000000	.9988026	.9896917	.9999799	00
PHENO-01		.248318E-3	.9159576	.9159576	.9159576	.4044983	00	00	00	5.67654E-3	.248318E-3	00	00
N-HEX-01		8.47340E-5	.0840423	.0840423	.0840423	00	00	00	00	5.20843E-4	8.47340E-5	00	.0204203
BENZE-01		1.93820E-3	00	00	00	.3157241	00	00	00	00	1.93820E-3	00	00
CYCLO-01		00	00	00	00	00	00	00	00	00	00	00	00
CYCLO-02		1.27921E-3	00	00	00	.2083779	00	00	00	00	1.27921E-3	00	00
N-HEX-02		4.18439E-4	00	00	00	.0681619	00	00	00	00	4.18439E-4	00	00
N-PEN-01		1.98759E-5	00	00	00	3.23769E-3	00	00	00	00	1.98759E-5	00	00
CYCLO-03		00	00	00	00	00	00	00	00	00	00	00	00
CYCLO-04		00	00	00	00	00	00	00	00	00	00	00	00
WATER		4.06475E-3	00	00	00	00	00	00	00	00	4.06475E-3	00	.9795796
CARBO-01		1.04610E-5	00	00	00	00	00	00	00	00	1.04610E-5	1.05697E-5	00
CARBO-02		9.41488E-6	00	00	00	00	00	00	00	00	9.41488E-6	9.51276E-6	00
TotalFlow	kmol/hr	6107740	.3801235	.3801235	.3801235	.3749482	6095601	6095601	6095601	6133613	6107740	6044901	.2534398
TotalFlow	kg/hr	1638400	4096000	4096000	4096000	3614164	1228800	1228800	1228800	1638400	1638400	1218987	5.799657
TotalFlow	l/min	6188053	.6485603	.6484688	.6484688	.6631654	24867.95	11360.46	24867.95	3260007	27995.46	24661.11	3.079849
Temperature	K	3531500	2987907	2981500	2981500	2981500	2981500	4763679	2981500	2956084	2981500	2981500	2981500
Pressure	atm	7895386	6.000000	1.000000	1.000000	1.000000	1.000000	3.500000	1.000000	7895386	1.000000	1.000000	1.000000
Vapor Frac		.9962439	00	00	00	00	1.000000	1.000000	1.000000	.9937462	.9981214	1.000000	.0208554
Liquid Frac		3.75609E-3	1.000000	1.000000	1.000000	1.000000	00	00	00	6.25382E-3	1.87856E-3	00	.9791446
Solid Frac		00	00	00	00	00	00	00	00	00	00	00	00
Enthalpy	cal/mol	2111120	-49742.15	-49784.04	-49784.04	-26023.66	2085282	1240998	2085282	-308.3235	-372.1405	-9646189	-70414.06
Enthalpy	cal/gm	7.869978	-461.6250	-462.0138	-462.0138	-269.9801	1084428	6156112	1084428	-115.4259	-138.7291	-4783501	-3077.031
Enthalpy	cal/sec	3581714	-5252.267	-5256.690	-5256.690	-2710.423	3.530847	21012.86	3.530847	-5253.160	-6313.715	-1619729	-4957.145
Entropy	cal/mol-K	-8.012387	-1.09.0722	-1.09.1651	-1.09.1651	-1.08.0778	-3.4884E-4	.7098417	-3.4884E-4	-9.385432	-5.020255	3.81852E-4	-4575851
Entropy	cal/gm-K	-2.986912	-1.01.2229	-1.01.3091	-1.01.3091	-1.121243	-1.7304E-4	.3818886	-1.7304E-4	-3.513587	-1.871485	1.8959E-4	-1.999605
Density	mol/cc	1.64504E-3	9.76839E-3	9.76977E-3	9.76977E-3	9.42319E-3	4.08531E-5	8.94271E-5	4.08531E-5	3.13579E-3	3.63615E-5	4.08531E-5	1.37149E-3
Density	gm/cc	4.41280E-3	1.052588	1.052736	1.052736	.9083113	8.23550E-5	1.80274E-4	8.23550E-5	8.37626E-3	9.75396E-5	8.23826E-5	.0313849
Average MW		2.682498	1077544	1077544	1077544	9639102	2.015880	2.015880	2.015880	2.671182	2.682498	2.016554	2288377
Liq Vol160F	l/min	5473085	.6809202	.6809202	.6809202	.6715978	5441116	5441116	5441116	5509208	5473085	5395860	1.006542

CONCLUSION

The biofuel production from the waste biomass is appealing. From low-energy-density biomass with a LHV of 2.2-2.8 MJ/kg(Edstorm et al) , a high value diesel fuel can be obtained. The biofuel obtained has a composition of phenol 40.45%, benzene 31.57%, cyclohexane 20.83%, N-hexadecane 6.82%, N-pentadecane 0.0032%. The other parameters of the biofuel are density 0.908gm/cc, enthalpy 269.9801 cal/gm and avg molecular weight 96.39.

The plant design offers possible solutions for and simplification of the issues of existing biogas plants. Because the digestate is directly converted after production in the biogas plant, no large storage tanks are necessary; the disposal problem could be solved, and at the same time fertilizer could be extracted from the waste water.

One method to increase the oil yield from the process would be to provide a digestate feed with a higher DM content to the HTL plant. This could be achieved, by not converting the input biomass fully in the biogas plant, but only converting the easily digestible part.

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